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Effect of small rivers for the inundations due to levee failure at Kinu River in Japan

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Abstract

On September 9, 2015, typhoon number 18 brought unprecedented rainfall to northern Japan, particularly to Kanto and Tohoku regions. As a result, flood damage and sediment disasters occurred in various locations including an overflow in Kinu River at Wakamiyado and levee failure in Kinu River at Misaka-cho. During the disaster, upstream of Kinu River has received more than 600 mm precipitation in 48 hrs which is more than twice the amount which usually received throughout the entire month of September. This unprecedented rainfall, has caused huge disaster to the people in Ibaraki prefecture particularly Joso city where the entire city has been recoded an inundation of about 1 - 2 m depth and it has been over 3 m in some areas. A small river (Hachikenbori River) flowing through the center of the flood plain was assumed to be the cause for earlier inundations in the downstream. We developed a coupled flood inundation model for the area with 1D and 2D hydrodynamic models, to study the effect of the Hachikenbori River for the inundations. The model includes the overbank flow and the flow due to river bank failure in Kinu River and Hachikenbori River. The developed model was validated with the observed data of inundations and water levels at Hachikenbori River. The results from the analyses performed with and without Hachikenbori River indicate that Hachikenbori River caused the early inundations in some places. Numerical results suggest that the Hachikenbori River has reduced the inundation area by 1 km^2 by allowing the flood water to pass quickly. However, there is no difference in the inundation heights of the cases carried out with and without Hachikenbori River.

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Keywords: Coupled 1D-2D models, flood inundation, Kinu River, river levee failure

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1. Introduction

Flooding is a very common disaster nowadays in many countries, particularly in Asia and the Pacific regions. Due to various issues including the practical limitation of collection of field measurements, numerical modelling of flooding is a vital step in finding the main causes of the flooding and its impacts to the surrounding community, as well as possible countermeasures. Coupled 1D and 2D models have been identified as suitable numerical models to simulate the complex nature

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of flooding over 1D or 2D models [1]. In recent times, frequency of the extreme rainfall events have increased, probably due to the issues resulting from the climate change. Due to its location, Japan faces number of typhoons annually, hence receives lots of rainfall around the country. Number of severe flood disasters has occurred in recent years. Defense works against flooding is very strong in Japan especially in urban areas. However, recent year's unprecedented rainfalls from typhoons have caused huge disasters in Isu Oshima (2013), Kansai area (2014) and Kanto and Tohoku regions (2015). Various countermeasures, both structural and non-structural forms have been implemented in Japan to reduce the damages. Also a number of studies on flood mitigations have been carried out by numerical simulations. This study focus on an analysis of the effects of a small river on flood inundations due to levee failure in a major River.

On 9th September 2015, typhoon number 18 landed to Aichi prefecture, central part of Japan and it brought unprecedented rainfall to northern Japan, particularly to Kanto and Tohoku regions. The heavy rainfalls resulted in severe flood damages and sediment disasters in many locations including an overflow of Kinu River at Wakamiyado and levee failure in Kinu River at Misaka-cho. Kinu River is originated from the pond Kinu in Tochigi prefecture and flows into Tone River that drains the largest river basin in Japan. During the disaster, Tochigi Prefecture received more than 600 mm precipitation in 48 hours which is more than twice the amount generally received in entire September. This unprecedented rainfall caused a huge disaster to the people in Ibaraki Prefecture, particularly Joso city where the entire city has been recoded an inundation of about 1 - 2 m depth and it has been over 3 m in some areas. As shown in Fig. 1 (a), Kinu River has started to overflow at Wakamiyado at 25.35 k and 24.75 k. After few hours levee started to collapse in Misaka-cho at 21 k. Initially the levee collapse was small as shown in Fig. 1(b) and then widen up to 200 m as shown in Fig.1 (c). This levee failure caused a large flooding damage over 40 km^2 area in the flood plain between Kinu River and Kokai River. The damage occurred not only in the vicinity of the levee failure but also the areas as far as 10 km away causing over 1300 people to be rescued by the rescue helicopters. However, downstream places were inundated before the flood water from the over bank flow and the river levee failure arrived through the terrain. This was supposed to be due to the flood flow through Hachikenbori River which is a tributary of Kinu River. In this study, we developed a coupled flood inundation model of 1D and 2D hydrodynamic models to study the effects of Hachikenbori River on the flooding. The model includes the overbank flow, the flow due to river levee failure of Kinu River and Hachikenbori River.

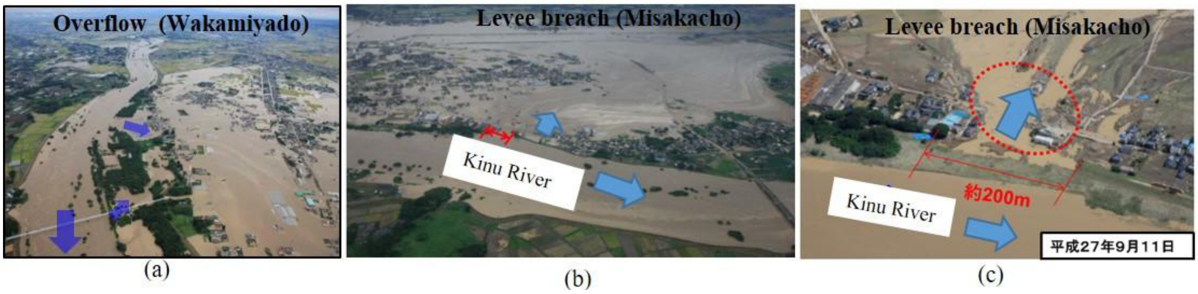

Fig. 1. (a) Overflow of Kinu River at Wakamiyado (b) Levee breach at Misaka-cho - initial stage (c) Levee breach at Misaka-cho – final stage (source-Ministry of Land Infrastructure and Tourism-Kanto section [2])

2. Study Location

The study location is Joso city in Ibaraki prefecture which lies in between the Kinu River and Kokai River. Kinu River originates at pond Kinu near the border between Tochigi prefecture and Gunma Prefecture and flows through Ibaraki prefecture into the Tone River that drains largest river basin in Japan. The Kokai River originates in a pond in Nasu-Karasuyama city in Tochigi Prefecture and flows into the Tone River at Tone town in Ibaraki Prefecture. The Kinu and Kokai Rivers are the longest and second longest among all tributaries of Tone River respectively. The combined basin area of the two rivers makes up a large proportion (17%) of Tone River basin. Kinu River is a 177 km of main channel length. Total basin area is 1761 km^2 [3] and 480000 persons live in probable flood areas. Annual average rainfall in Tone River basin is 1300 mm whereas the annual average rainfall in Japan is 1700 mm. However, regional distribution of annual rainfall in Kinu and Kokai river basins show a wide variations which is 1600-2000 mm in mountain areas and 1200-1400 mm in plain areas. Snow as well as rain is an important source of water of Kinu River. The mountain areas receive snowfall as the northwestern seasonal winds and low pressure centers pass along the southern coast of Honshu and snow accumulation of 10 cm or more lasts for 30-50 days. The cumulative snowfall is about 210 cm in Nikko. Kinu River basin has undergone floods in past years mainly due to the torrential rain caused by typhoons in 1935, 1938, 1947, 1949, 1982 [4]. However, the maximum rainfall amount for consecutive days were much smaller than the rainfall amount in 2015 flood event [2].

3. Methodology

In the analysis, a coupled 1D and 2D hydrodynamic model was developed for the area to incorporate Hakeknbori River and the flood plain. Field observations on the flood inundations, flood situation and Hachikenbori River cross-sections were carried out. MIKE 11, MIKE 21 and MIKE FLOOD were used as the 1D, 2D and coupling models respectively in the calculations. ARCGIS was used as the geo processing and mapping tool. As shown in Fig. 2, the calculation area was selected in north-south direction to get the same area as the track record of inundation area. The grid sizes in the north-south and east-west directions are 50 and 100 m respectively. The overflow at Wakamiyado and the discharge due to the levee failure were given as the boundary conditions. The discharges from Wakamiyado and Misaka-cho were calculated taking account of the water level at Kinu River at Kamaniwa point (27.34 k). Since the levee failure occurred gradually and the discharge varied gradually, it was calculated as a time series data considering the change in opening width of the levee failure location from 20 to 200 m. Fig. 3(a) shows the discharge from the overflow point and levee failure point. Pumping at Hakkenbori mouth was given as shown in Fig. 3(b).

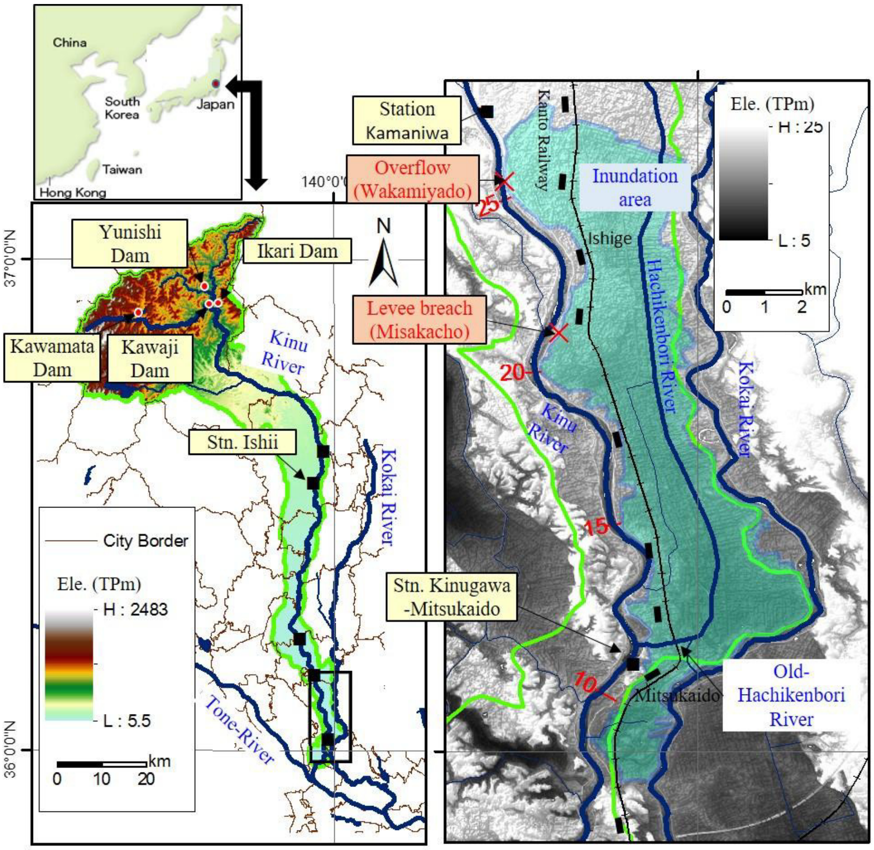

Fig. 2. Study area and model domain

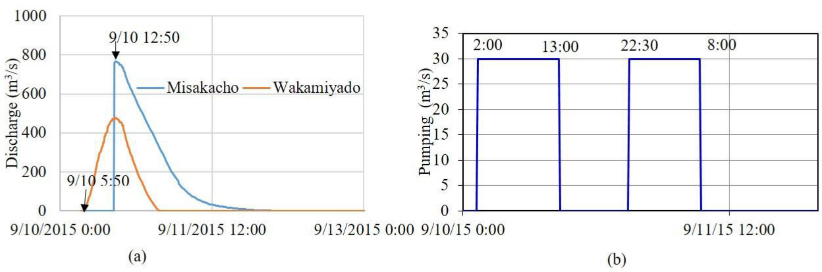

Fig. 3 (a) Discharge from overflow and levee failure (b) Pumping discharge

Elevation data for the mesh were obtained from 5 m DEM obtained from Geospatial Information authority of Japan (GSI). For the embankment for the highway and the railway, elevation value was given by subtracting 40 cm from the maximum value in the mesh. For the roughness coefficient 0.08 $m^{-1/3}s$ and 0.12 $m^{-1/3}s$ was used for rural areas and urban areas respectively. Simulations were carried out from 2015/09/10 5:00 am to 2015/09/11 8:00 am. Upstream discharge of the Hachikenbori River was calculated from MIKE 11 RR model URBAN A. It was given as the upstream boundary of the Hachikenbori River. Pumping data at Hakkenbori mouth from the operation records as shown in Fig. 3(b) and the water level at Kinu River at Mitsukaido station was given as the downstream boundary of the Hachikenbori River.

3.1. Numerical method and the governing equations

The main governing equations of MIKE 11 and MIKE 21 models, and the solution procedures are briefly discussed in here. The governing equation of 1D model is Saint Venant equation based on the assumptions that incompressible and homogeneous fluid, uniform velocity and horizontal water level in cross section, small bottom slope and small longitudinal variation in hydrostatic pressure distribution. The equations are conservation of mass and momentum as given in Eqs. 1 and 2 respectively.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

where A is flow area, t is time, Q is discharge, x is horizontal distance and q is lateral inflow.

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\alpha\frac{Q^2}{A}\right)}{\partial x}+gA\frac{\partial h}{\partial x}+\frac{gQ[Q]}{C^2AR}=0 \tag{2}$$

where α is momentum distribution coefficient, g is gravitational acceleration, h is free surface elevation, C is Chezy resistance coefficient and R is hydraulic or resistance radius.

The solutions of the equations of continuity and momentum is based on an implicit finite difference scheme [5]. The scheme is structured in order to be independent of the wave description specified (i.e., kinematic, diffusive or dynamic). The modelling system of MIKE 21 is based on the numerical solution of the depth averaged Navier Stokes equations describing the conservation of mass and momentum in two horizontal directions. These equations can be written in simplified form as given in Eqs. 3-5 respectively.

$$\frac{\partial h}{\partial t}+\frac{\partial(ud)}{\partial x}+\frac{\partial(vd)}{\partial y}=S \tag{3}$$

where u and v are the depth averaged velocities in x and y directions respectively, d is water depth and S is source term respective to direct rainfall.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial h}{\partial x}+\frac{gu\sqrt{u^2+v^2}}{C^2d}-E\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=0 \tag{4}$$

where E is an eddy viscosity coefficient.

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial y}+u\frac{\partial v}{\partial x}+g\frac{\partial h}{\partial y}+\frac{gv\sqrt{u^2+v^2}}{C^2d}-E\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)=0 \tag{5}$$

These equations are solved using finite difference approximations and an Altering Direction Implicit (ADI) scheme [6] [7] these include unconditional stability in the linear sense where there is no stability limit on the time step [8].

3.2. Filed observations

Very extensive field survey was carried out by the members of Hydraulics laboratory, Tokyo University of Science regarding the flood inundations. Initial investigations were carried out on 10 September 2015 to have an overview of the flood situation. This was a reconnaissance survey of the flooding range and found the initial flooding in the Mitsukaido district which was supposed to be due to the flow through the Hakeknbori River. After that, detailed inundation surveys were carried out on 15 and 16 September and 14 October 2015 for inundation depths and the positions. Inundation depths were obtained by tracing the water marks on existing buildings, trees and sloping grounds. The heights were measured using a staff. Ground elevation and positions were traced using RTK GPS instruments (Trimble R4 and Trimble R6; Manufactured by Trimble). The accuracy of these instruments are up to several centimeters both horizontal and vertical directions. In addition to the survey results by the Tokyo University of Science, Sayama et al.,[9] data were also used in the analysis. Altogether, data were obtained from 307 points including elevation measurements at 133 points. Moreover, information from the local residents of Mitsukaido district and photos taken during the field surveys were used to understand the flooding situation. Also, a cross sectional survey at Hachikenbori River was carried out to model the river hydrodynamics accurately. Field survey results indicated that, the inundation was along a wide range from overflow point at Wakamiyado to Mitsukaido district. Near Wakamiyado area inundation ranged from 0.5 - 2 m. The vicinity of Misaka-cho (the levee break point), inundation depth was maximum of 3 m. Downstream areas especially near the Hachikenbori River, inundation depths were up to 3 m. Maximum of 3.01 m inundation depth was observed in the downstream areas of Hachikenbori River [10].

4. Results and Discussion

Results of the numerical model and the data from the field survey are discussed here. Coupled 1D and 2D hydrodynamic model results of inundations were compared with the data obtained during the field surveys. Results are discussed in the section 4.1. Analysis with and without the Hachikenbori River is discussed in section 4.2.

4.1. Verification of the Model

Fig 4 (a) shows the difference of simulated and observed inundation depths in the calculation domain. Right hand side of 4(a), indicatess the respective correlation plots of the inundation depths. From the figure, we can see that in the upper and middle parts, simulated and observed data have a good correlation. However, in the downstream areas, simulated data are slightly overestimated. The reason for this overestimation is probably due to the presence of another small channel which was not consider in the analysis. Further, Fig. 4(b) shows the water levels of Hakeknbori River at Misaka-Shinden (6 km from river mouth) and Hakkenbori mouth locations. Results indicate that the simulated and observed data are consistent with each other.

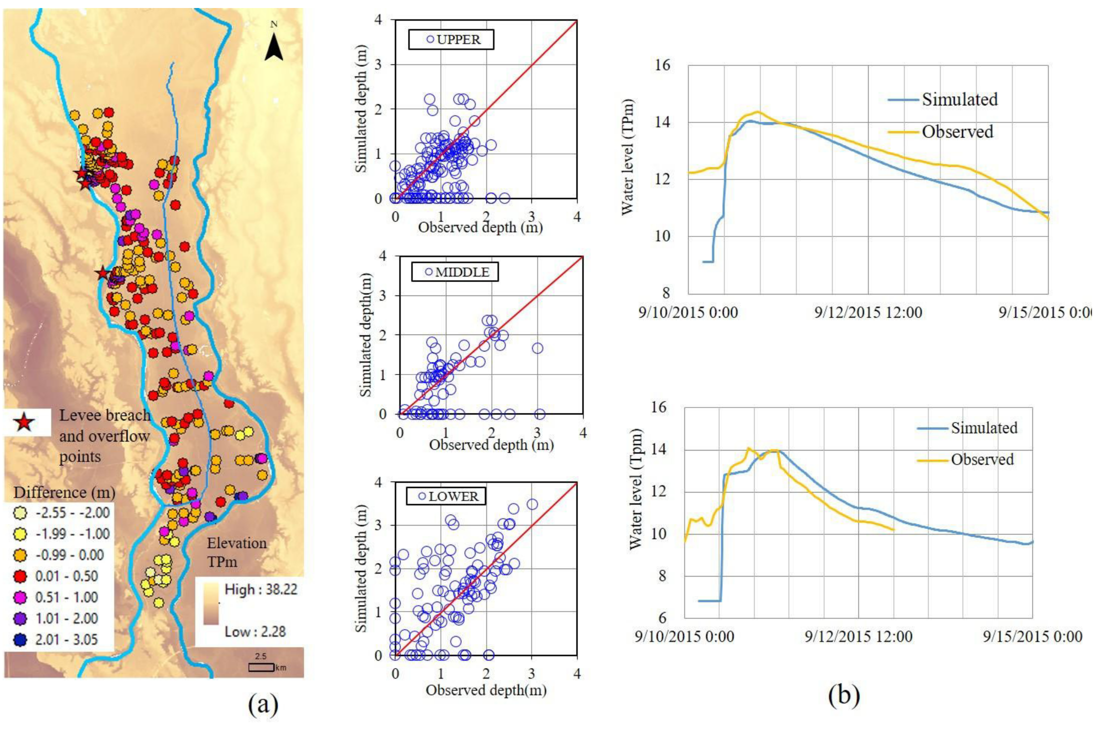

Fig. 4(a) Difference of simulated and observed inundation depths(left) and correlation plots of simulated and observed inundation depths (right) (b) water levels at Hachikenbori River (upper - at Misaka-Shinden 6 km from Hachikenbori mouth, lower – at Hachikenbori mouth)

4.2. Analysis of the effect of Hachikenbori River on inundations

The verified model was simulated with and without the Hachikenbori River to analyses the effects of Hachikenbori River on the inundations. The inundation maps obtained are as shown in Fig. 5. As shown in the Fig. 5, inundations started at Wakamiyado due to the overflow from the Kinu River. Overflow was started around 5:50 am on 10 September 2015. Then the flood gradually propagated downstream and around 12:50 pm on the same day the levee was started to breach in Misaka-cho. Around 2:00 pm on the same day as can be seen in the Fig. 5, flood propagated downstream and earlier inundations at most downstream can be seen with the case of Hachikenbori River. This early inundations cannot be seen in the case of without Hachikenbori River. Therefore, it is clear that, the Hachikenbori River caused for the earlier inundations in the downstream, allowing a fast flow through the Hachikenbori River. Around 5:00 pm on the same day the main flood flow has reached Mitsukaido district as can be observed in both cases. Around 11:00 pm on the same day, flood flow has reached to the Hakkenbori mouth covering almost all of the flood plain. Since the flood gates at Hakkenbori mouth was closed and only pumping was operated at that time, from 11:00 pm to 8:00 am on next day, the flood was accumulated and inundation depth has reached to a maximum by 7:00 am on 11th morning. After 8:00 am on 11 th morning, the flood gate at Hakkenbori mouth was opened allowing the flood flow to Kinu River. We have heard that, the small scale early flooding caused people to stay home thinking it is a small flood and when the larger flood wave approach their houses, many people couldn't escape suddenly. This cause large number of people to be evacuated by rescue helicopters and boats.

As observed from the field surveys, there were places inundated due to the flow through the drainage canals which were opened during the flooding time. However, since the drainage network was not modeled in the simulation those are cannot be seen in the results. The highest inundations were observed in the downstream areas of Hachikenbori River. Some of them are due to the Old Hachikenbori canal which was used to be the Hachikenbori River in early times. At that time the river water of Hachikenbori River was directed to Kokai River. Now that canal has a gate at Hachikenbori River and a pumping station near to Kokai River. However, during the flood it was supposed that the flood gate at Hachikenbori River for the Old Hakkenbori canal was opened and much water was flowing in that direction. Since the pumping station of the Old Hachikenbori River which pumps water to Kokai River is in low elevation, when the flood is higher the pump house cannot be operated well.

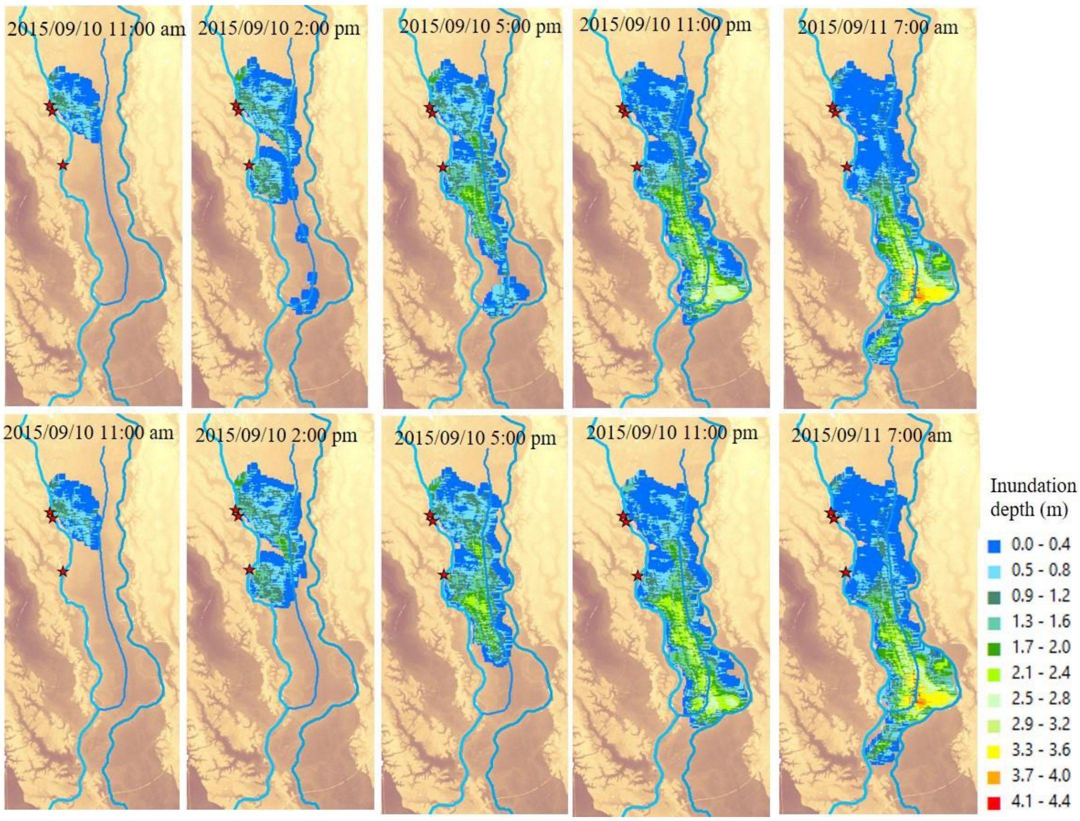

Fig.5 Inundations of the area with the Hachikenbori River (upper) and without Hachikenbori River (lower)

5. Conclusions

A coupled 1D and 2D hydrodynamic model was developed for the inundation analysis for the Joso city area including the flood plain between Kinu and Kokai Rivers and the Hachikenbori River which flows through the center of the flood plain. Developed model was verified with the observed data of inundation data around the flood plain and water levels along the Hachikenbori River.

Model was used to study the effect of the Hachikenbori River for the inundations in the downstream areas. The results indicate that the flood flow from a levee failure reached Hachikenbori River and propagated to the downstream faster and caused some early inundations in the downstream areas before the main flood waves arrived. The results also suggest that the maximum inundation heights of the cases of with and without Hachikenbori River do not have any significant differences. The results indicate that the inundation area is smaller in the case of with Hachikenbori River than the case of without it. However, the difference is very small (about 1 km^2) and therefore it is negligible compared to the total inundation area (40 km^2).

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